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Original Article

Development of an information reference system using reconstruction models of nuclear power plants

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A B S T R A C T

Many nuclear power plants in Japan are approaching the end of their planned operational life spans. They must be decommissioned safely in the near future. Using augmented reality (AR), workers can intuitively understand information related to decommissioning work. Three-dimensional (work-site) reconstruction models of dismantling fields are useful for workers to observe the conditions of dismantling field situations without visiting the actual fields. This study, based on AR and work-site reconstruction models, developed and evaluated an information reference system. The evaluation consists of questionnaires and interview surveys administered to six nuclear power plant workers who used this system, along with a scenario. Results highlight the possibility of reducing time and mitigating mistakes in dismantling fields. Results also show the ease of referring to information in dismantling fields. Nevertheless, it is apparently difficult for workers to build reconstruction models of dismantling fields independently.

1. Introduction

Many nuclear power plants (NPPs) are approaching the end of their operational life spans. After the Fukushima Daiichi accident, all NPPs in Japan ceased operations. Most have remained halted. To resume operations, NPPs must meet new regulatory requirements, but most small-scale NPPs are being selected for decommissioning instead. Many NPPs must be decommissioned in the near future.

Before dismantling work, a detailed plan must be made. Because of possible residual radioactivity, workers must then follow the dismantling plan carefully. Concretely, a field supervisor, who gives work directions, first visits a work site to ascertain its condition. Based on his/her own knowledge and experience, the field supervisor then decides which parts should be cut, how the area should be decontaminated, what work procedures to use, and so on. The dismantled equipment is arranged temporarily while radioactive residues are measured. Because NPPs are known to have many narrow areas, the field supervisor also examines the routes used to convey bulky equipment. Therefore, the field supervisor must clearly understand the work-site situation. However, to reduce radiation exposure during dismantling work planning, one must decrease the number of site visits and must reduce, to the greatest extent possible, the time spent in the area itself. For actual dismantling work, workers must grasp information such as the operational status and existence of residual water in the dismantling objects. Moreover, decommissioning is long-term work, lasting decades. Therefore, younger employees must inherit expertise from experienced workers.

As expected from the aforementioned section, reducing exposure amounts and work mistakes and providing expertise to young workers are important. Support systems using augmented reality (AR) are expected to increase safety and efficiency in dismantling work because users can intuitively ascertain real-world relations between objects and their related information [1]. Recently, making three-dimensional (work-site) reconstruction models of work sites has become easy. By virtue of using RGB-D cameras, which can obtain not only RGB images but also depth images, models can reflect the actual work-site situation. By capturing work-site details, reconstruction models can be produced to reflect even small facilities that do not exist in CAD models. They can also reflect current detailed situations that past CAD models have not reflected because

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of facility renewal. Once these reconstruction models have been made, one can verify the work-site situation at any time without a site visit. Information that workers want to refer to can be annotated on dismantling target objects of the models. Then, that information can be communicated easily by displaying it using AR. Furthermore, the information can be saved as electronic data, making past information accessible and searchable, thus providing useful guides for younger workers when planning dismantling work. The models are also useful for preparation using model-based tracking.

Using reconstruction models at work sites can help users confirm work sites and help them share and inherit information. Reconstruction models can also support AR.

This article presents the study purpose in Section 2. Section 2 explains the proposed information reference system and its three subsystems. In Section 3, the subsystems described in Section 2 are evaluated. In Section 4, a summary and future works are described.

The purpose of this study is the development and evaluation of an information reference system using reconstruction models and AR that can be available during NPP dismantling work. The developed system has the following two features.

1. By virtue of reconstruction models reflecting details of the work-site situation, work-related information can be produced and recorded without visiting work site.
2. Workers on site, using AR, can refer to work-related information with an intuitive and concrete relation to the target instrument.

For evaluation, a trial was conducted with workers doing dismantling work. The system and system-related difficulties were investigated during actual dismantling work.

2. Information reference system

This section explains the overall information reference system. Three subsystems and their functions in the system are described.

2.1. Overview of the system

Fig. 1 presents an overview of the information reference system developed for this study. It has three subsystems: the Modeler, Annotator, and Viewer. With the Modeler, 3-D reconstruction models are made using RGB-D images captured at the work site. The models reflect current situation details. With the Annotator, using a desktop computer, the user can virtually visit the work site and can annotate information related to dismantling work. The items and choices of information that the user can input were chosen based on opinions of workers who actually perform dismantling work. In addition, the Annotator has a function of simulating the layout of vessels used for storing dismantling wastes. Using the viewer on a tablet computer, an on-site user can refer to information annotated by the Annotator. This information is displayed superimposed with AR. Using these subsystems decreases the number and duration of site visits when considering and producing work plans. It encourages information sharing among workers and also facilitates information comprehension during dismantling work. Each subsystem is used by field supervisors and workers. Therefore, these subsystems must be developed carefully so that even workers with no knowledge of computers can use them easily.

2.2. Modeler

To produce reconstruction models, various methods are available, such as using an RGB camera [2], using an RGB-D camera [3], and using a laser scanner. For this system, we used a method with an RGB-D camera [4]; because it is a small and useful device, it can be brought into an NPP and can produce detailed reconstruction models. However, the use of this method is a trial. We are developing another method to produce future reconstruction models. Reconstruction models are downsampled using Quadric Clustering [5] to produce resolution of approximately 1 cm for each dimension and to reduce the data volume.

2.3. Annotator

Using the Annotator, a user can check the reconstruction models produced by the Modeler. The Annotator has three functions:

1 information-adding function
2 distance measurement function
3 layout-simulating function for vessels storing dismantling waste materials

These functions were chosen based on NPP worker opinions. Fig. 2 presents an Annotator screenshot. The Annotator main screen has two parts: reconstruction model view and operation window. The reconstruction model view displays reconstruction models using the Visualization Toolkit [6]. The operation window includes buttons to produce a new file, save and load files, change and reset

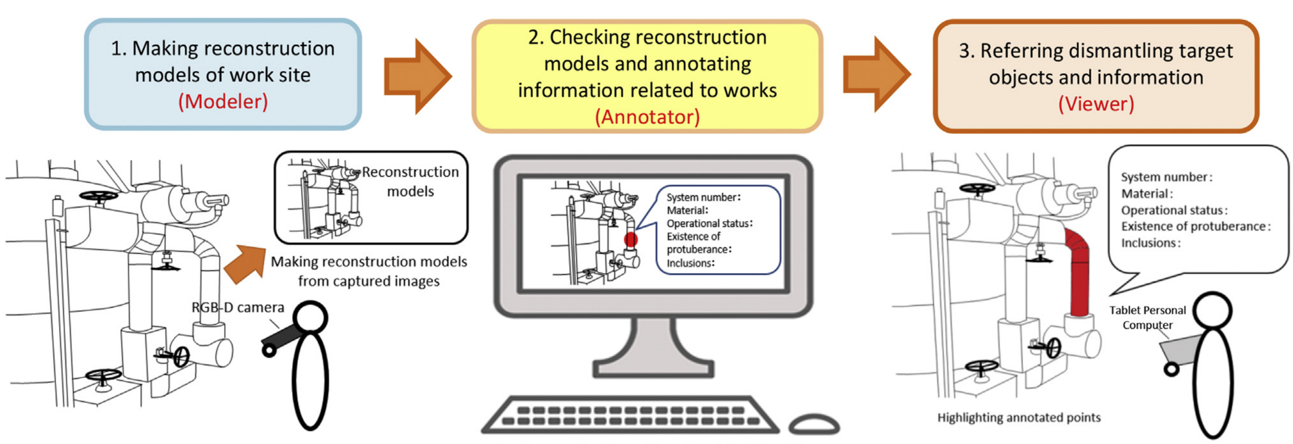

Fig. 1. Overview of information reference system.
PC, personal computer.

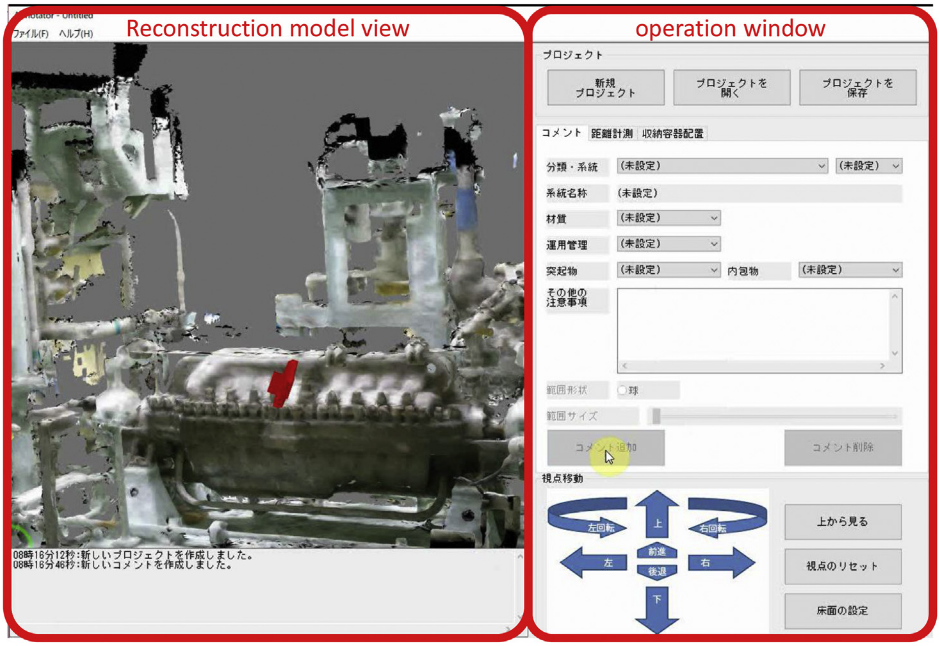

Fig. 2. Screen shot of the Annotator.

viewpoints of the reconstruction model view, and set the floor surface. The operation window includes an information description tab, a distance measurement tab, and a vessel layout tab. Fig. 3 presents an screenshot of the distance measurement function in a distance measurement tab.

After selecting the information description tab, a user can place the cross-shaped cursor by left-clicking at any point of the model. By pushing the button to add information, a user can place a virtual tag at the point of the cursor. At this time, an information input form appears on the operation window. A user can input notes for dismantling work with information on six items: 1. system number and name of facility; 2. material; 3. operational status; 4. existence of protuberance; 5. inclusions; and 6. other notes. To ease user recognition of points at which tags are placed and their states, the chosen tag is red. Others are blue and yellow so that users can notice them easily.

When selecting the vessel layout tab, a user can simulate the layout of vessels used to store dismantling wastes, but it is necessary to set up the floor in the reconstruction model in advance because the vessels are put on the floor. In this system, using RANSAC [7], by choosing any point of the floor, the floor is recognized automatically by plane recognition. RANSAC is an algorithm to estimate parameters of a mathematical model. After the recognition, by left-clicking at any point of the floor, the cross-shaped

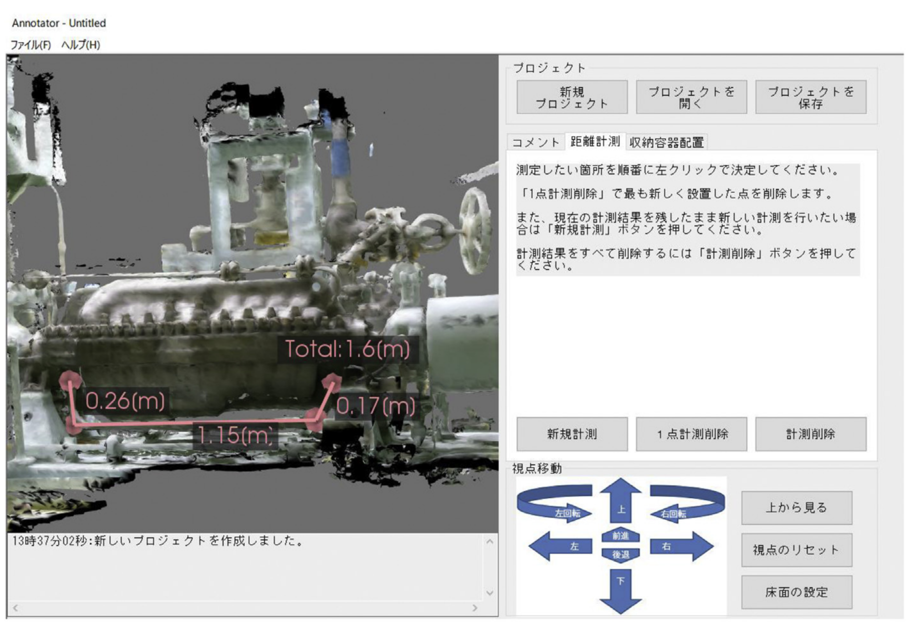

Fig. 3. Screen shot of the distance measurement function.

cursor is placed, and the user can place a virtual vessel. Using a pull-down menu, radio button, and slide bar, the user can change the vessel type, the number of tiers, and the direction. The user can also move the vessel along the floor by dragging on the model display screen. This subsystem can detect collisions among vessels and facilities in real time. When collisions occur, the vessel color changes to inform users.

Users can save these results to a file. By loading this file, a user can refer to the information using the Viewer.

2.4. *Viewer*

Fig. 4 presents a screenshot of the Viewer. The Viewer display has three parts: a camera view, an operation window, and an information window. Surface 3 (Microsoft Corp.) is used as the Viewer hardware. The camera view displays camera images in real time. The virtual tags and vessels are displayed in camera view according to the current position and direction of the camera. Selecting tags on the camera view using a stylus pen, a user can see the information of the selected tag in the information window. In the operation window, there are buttons to load files and to stop and restart the updating of camera images. When watching the work places and notes with the Viewer, holding a camera toward the work object might be a burden for workers. Therefore, we implemented a function to stop and restart the updating of camera images.

In the Viewer, using AR, the tags and vessels are displayed by superimposition at the correct positions. In this system, model-based tracking with reconstruction model is used so that the user can use AR without placing AR markers at the work site. However, as described later, we used AR markers for tracking to reduce the preparation time when evaluating this system.

When using the Viewer, by selecting the button to load files and by selecting files made using the Annotator, the selected files are loaded, and the placed tags and vessels are superimposed. The vessels are displayed with the reflecting type, number of tiers, and direction set by the Annotator.

3. Evaluation of the system

3.1. *Purpose of evaluation*

Objectives of the evaluation are to assess the usability for actual real dismantling work and to identify difficulties of its application to actual dismantling work.

Fig. 5. Appearance of the charging pump room.

3.2. *Method of evaluation*

For this evaluation, six Fugen Decommissioning Engineering Center workers used the developed system along with a scenario in a charging pump room in a controlled area and a conference room. Using the heuristic method, the utility was evaluated using questionnaires and interview surveys. Fig. 5 depicts the charging pump room.

Fig. 6 portrays the evaluation procedure. The experimenter explained the whole evaluation process in advance. Then, trials, questionnaires, and interview surveys, respectively, related to the Annotator, the Viewer, and the whole system were conducted. Earlier examinations showed that the Modeler was difficult for workers to use.

In the earlier examinations, to produce reconstruction models in a charging pump room, the field supervisor used the Modeler after our explanation of the Modeler; for example, we asked him to move the RGB-D camera slowly and capture the entire charging pump room. However, the field supervisor still moved the RGB-D camera quickly, and some parts were not captured appropriately. Therefore, the quality of the reconstruction model produced from the captured data was poor. Results show that with the current version of the Modeler, a reconstruction model cannot be produced with which a supervisor can check the details. Some improvements such as introducing a navigation function to instruct in ways to capture the entire work environment are needed. Therefore, the Modeler was excluded from this evaluation, and only the Annotator and

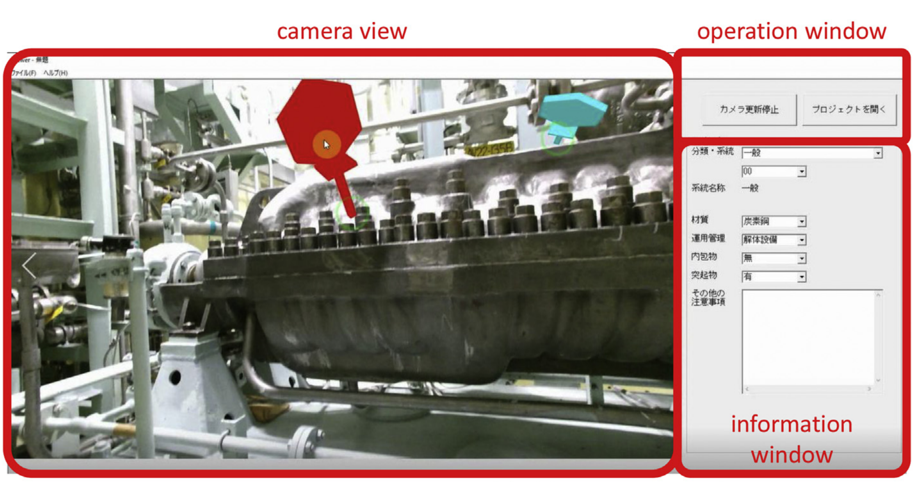

Fig. 4. Screen shot of the Viewer.

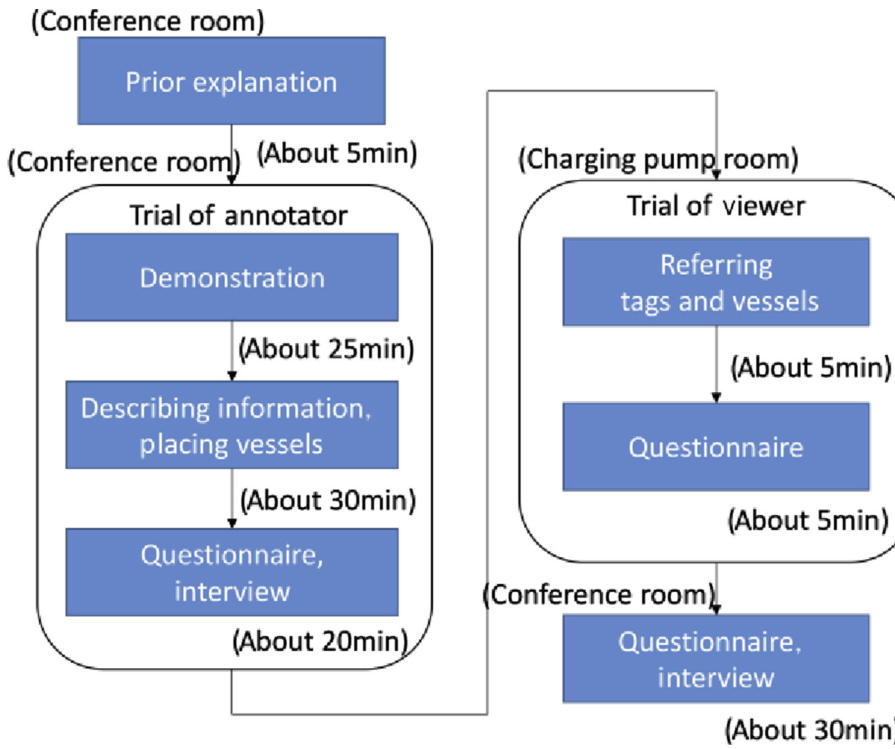

Fig. 6. Flow of experimental evaluation.

Viewer were evaluated. During trial use of the Annotator, a charging pump room model was made in advance. A sensor (Kinect; Microsoft Corp.) was used to make this reconstruction model. In the Viewer trial, AR markers [8] were placed for tracking to reduce the preparation time.

In the Annotator trial, the experimenter first demonstrated each Annotator function. After the demonstration, six workers tried the Annotator in the conference room. For the scenario of this trial, the field supervisor was asked to annotate information related to dismantling work and simulate the layout of vessels storing dismantling wastes so as to avoid interfering other facilities. The subjects placed tags on the model of the charging pump room, described related necessary information, and saved these results to a file. Then, they placed vessels in the room model resembling the work site. They saved their results to another file. During this trial, they used all functions of the Annotator, along with the task list, irrespective of the order. They decided the locations of tags on their own. They also placed as many vessels as they needed. Finally, the experimenter administered questionnaires and interview surveys related to the usability of each function. Questionnaire items were answered on a scale of one to five. In interview surveys, the experimenter asked for reasons for their answers to each item. The left column of Table 1 shows Annotator question examples.

For the Viewer trial, the experimenter explained each Viewer function in the charging pump room. Then, workers tried the Viewer one by one at two charging pump room locations. For the scenario of this trial, the worker was asked to check information that the field supervisor or the former worker had annotated. The worker was also asked to check the layout of vessels. Evaluators loaded a file including notes and vessels. Each tag had information such as that the material was carbon steel, residual water was included, and the facility remained working. Participants then used a stylus pen and selected the tag displayed by superimposition on the camera images to refer to notes. They also confirmed vessels displayed by superimposition on the charging pump room floor. The vessels that had one tier and two tiers were placed in the charging pump room. Participants then answered questionnaires in the charging pump room. We interviewed them to determine the reasons for their answers to each item in the conference room. The left column of Table 2 shows some Viewer questionnaire items.

After the trial and after Annotator and Viewer questionnaires and interview surveys, the experimenter administered questionnaires related to the entire developed system. Later, the experimenter interviewed respondents about the reasons for their answers to each item. The left column of Table 3 shows items for the whole system questionnaire.

3.3. Results and discussion

For the evaluation, prior explanations took about 5 min, the Annotator trial took about 75 min, and the Viewer trial took about 10 min. Questionnaires and interview surveys about the whole system took about 30 min. Table 4 presents the main results of the evaluation.

To confirm the consistency of these results, we calculated intraclass correlation coefficients for the questionnaire results; these coefficients are shown in the right columns of Tables 1–3. The intraclass correlation coefficient was 0.0182, which means these results did not have consistency. Therefore, we investigated in greater detail the questionnaire answers to which the evaluator answered with a response worse than 4, especially based on the free description and the interview.

The results of questionnaires and interviews showed that reconstruction models in the Annotator looked rough; when the user zoomed in, the model was obtained. Reconstruction models used in the evaluation were insufficient to be observed in detail. In the evaluation, in consideration of the PC performance, models were downsampled using Quadric Clustering so that the data size

Table 1
Examples of the Annotator questionnaire items.

Questionnaire item	Evaluator					
	A	B	C	D	E	F
• You were able to check displayed model details.	4	4	4	2	2	5
• You were easily able to describe information related to dismantling work.	5	5	5	4	3	5
• You were able to place vessels at intended points.	4	5	5	4	3	5
• First-time users can use the system easily.	4	5	3	3	3	5
• You were easily able to move viewpoints rotationally by clicking rotate button.	2	5	4	3	2	3
• You were easily able to move viewpoints by dragging the mouse using the right button.	5	5	4	3	4	5
• It was effective to move viewpoints by dragging the mouse using the right button.	5	5	5	3	4	5

Table 2
Examples of the Viewer questionnaire items.

Questionnaire item	Evaluator					
	A	B	C	D	E	F
• You were easily able to understand points at which the tags were placed.	5	5	5	4	3	3
• It was easy to refer information by choosing tags in the camera view.	5	5	5	5	3	5
• You were able to understand easily the points at which the vessels were placed.	4	5	5	5	2	5
• First-time users can use the system easily.	5	5	5	5	3	5
• The camera view size was appropriate.	5	5	3	5	3	1
• The Viewer display size was appropriate.	4	4	3	5	3	5
• The button sizes were appropriate.	3	5	5	5	3	3
• The displayed character sizes were appropriate.	4	5	3	4	3	3
• Displayed information was comprehensive.	5	5	5	5	3	5

Table 3
Examples of whole system questionnaire items.

Questionnaire item	Evaluator					
	A	B	C	D	E	F
• The time of visiting work sites seems to be shorter when using the Annotator.	4	5	4	4	4	3
• Work mistakes seem to be reduced when using the Viewer.	5	5	4	4	4	4
• The system seems to be more effective than paper medium.	4	5	5	5	4	4

Table 4
Main evaluation results.

- Changing viewpoints by mouse operation was easy and effective.
- Distance measurement functions would be useful at narrow places and at places where it is difficult to operate dismantling devices.
- The system would be better if a user were able to measure the surface area and volume using the Annotator.
- The system would be better if a user were able to annotate information in the Viewer as in the Annotator.

was not big. We can use more detailed models if we use higher performance PCs.

Regarding the function of changing viewpoints, results showed that changing viewpoints by mouse operation was easy and effective, but the axis of rotation was difficult to understand when using button operation. Operation by mouse was faster than that using buttons. In the development phase, we thought that a user would be able to change viewpoints intuitively using buttons. Results showed that the mouse operation was more intuitive and suitable. Users reported that it would be better to be able to change the user viewpoint in parallel by mouse. Therefore, it might be easier to use mouse operation only to check models with a viewpoint change system.

Regarding the function of measuring distances, this function was expected to be useful in narrow areas where it was difficult to operate dismantling devices. Results showed that this function was useful. It was reported that the system would be better if a user were able to measure not only the distance but also the facility surface areas and volumes. It was reported that the system would be better if a user were able to place vessels, scaffolding, and devices for dismantling.

For the Viewer, the application screen size, buttons, and characters were reported to be small. The work site is dark with poor visibility. In addition, workers must wear gloves. Therefore, display buttons and characters should be larger than those used in an office. In reference to the described information, the placed locations of tags and the descriptive information were reported to be comprehensible. However, work-site facilities were reported to be hidden by superimposed tags. Therefore, the shapes and sizes of tags must be reconsidered, along with the display; changes might include using wire frame models instead of solid models. We received reports that users describe information that is unique to workers visiting work sites, such as how workers coped with past cases, by making a system similar to the Annotator to describe information. Therefore, we found that system utility would be improved by introducing a function to describe work-site information. However, when introducing this function, some ideas, such as fixed phrases, are needed to describe information easily because it is necessary to reduce the length of visits to work sites.

For the whole system, the Annotator was reported to be useful because it could reduce the duration of work-site visits if difficulties related to the interface were improved. For the Viewer, workers were able to reduce mistakes by using this subsystem. However, considering each function in greater detail, many technical problems arose, such as ways of displaying tags, and improvements were suggested related to the functions described previously. Regarding the Modeler, workers reported difficulty using this system to produce high-precision reconstruction models. Therefore, the system needs to be able to produce reconstruction models easily; this can be accomplished by improving future versions of the Modeler.

4. Summary

In this study, we strove to improve dismantling work safety and efficiency at an NPP. We developed an information reference system using reconstruction models and AR. Then, based on responses to questionnaires and interview surveys with NPP workers, we evaluated the system utility and investigated difficulties arising when applying the system to actual dismantling work. Evaluations revealed that reduction of the work-site visit duration and decrease of mistakes in work can be expected. Future studies must produce a system with which workers can produce reconstruction models easily. It is also considered that users would set up more detailed and effective dismantling plans if this system had a function to calculate radioactivity from the amount and the layout of dismantling waste. If this function is introduced, the usability of the developed system would be increased in actual dismantling work.

Conflict of interest

There is no conflict of interest.

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